

DESIGN AND IMPLEMENTATION OF AN ESP32-BASED SEMI-AUTOMATIC ROAD SWEEPING SYSTEM

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Abstract

In Public health, environmental protection, and urban infrastructure, road cleanliness is ensured. Traditional manpower-based sweeping methods are inefficient and unsuitable for larger areas. This project deals with the design and development of a semi-automatic road sweeping system. The developed system includes mechanical architecture and embedded control that makes the cleaning more efficient and faster. It also does not require too much manual effort. The proposed system consists of 12V high-torque DC gear motors, which are provided for a four-wheel drive. It can move in multiple directions. A brush motor is provided, which will rotate above the surface for cleaning dust and debris from the surface. A relay module that facilitates manual and semi-automatic operation of motors is still a control unit based on an ESP32 microcontroller. A 12V, 7Ah lead-acid battery powers the system, which is portable and operational. According to tests, the robot has stable mobility, cleaning efficiency on dry surfaces, and system performance. The robot speed is around 1.3 km/h with a run time of 45–50 minutes. Compared to conventional methods, the suggested system consumes less human effort with better cleaning. The prototype that was developed can be used on urban roads, highways and industrial locations and is compact and cost-effective, and easily scalable to demand. The prototype can also be IoT automated and made smart city compatible.

Keywords:

Semi-Automatic Road Sweeping System, Embedded Control (ESP32), DC Gear Motor Drive System, Smart Cleaning Technology, Urban Road Maintenance

1. INTRODUCTION

One of the most important needs for the welfare of the people, the environment, and urban standards is road cleanliness. The relation between intensified urbanization, rise in industrialization, and increase in vehicles on roads has played a prominent role in the accumulation of dust, dirt and filth on the roads and highways. Poor waste management harms the environment. In addition, it causes air pollution, traffic obstacles and ill health from exposure to dust and other contaminated matter. Traditional road cleaning mainly relies on manual sweeping, which is labor-intensive and time-consuming. Moreover, it is not very effective and is inefficient for large-scale applications. In addition, the workers are also exposed to hazardous environments, including dust inhalation and unsafe traffic. Despite enhancing efficiency and lessening human involvement, the high cost, complex maintenance, and accessibility issues of fully automated road sweeping machines limit their use in developing countries and small municipalities [1], [2].

Recent innovations in robotics and embedded systems have led the way to the inception of autonomous and semi-autonomous cleaning machines that incorporate IoT, smart navigation and path planning techniques [3], [4]. Nonetheless, most of the existing systems are costly and fully autonomous or mostly indoor

designed, so that these cannot be used for road cleaning. Many solutions are also complex, costly, and do not work in real-time. This exposes an important research gap in developing a compact, low-cost and semi-automatic road sweeping system that is capable of good functionality and viability.

To overcome this shortfall, the present study adopts a semi-automatic road sweeping machine which consists of a four-wheel Drive mechanism and an ESP32-based embedded control unit. To facilitate movement, the system uses high-torque DC gear motors. The mechanism to remove garbage is a rotating brush. The controlling system is a relay-based interface. The system has a manual mode and a semi-automatic mode. The vehicles' design is not only cost-effective but also lightweight and easy to maintain. According to the experimental validation, it was found that the system under consideration has better cleaning efficiency, less human effort and stable operational characteristics. Therefore, the system can be used on roads, highways, industries, etc. Further scope of development can be made for IoT-enabled automation and smart cities.

The innovation of this research is that it proposes a novel semi-automatic road sweeping device that can be a good balance between manual and fully automatic devices because of its effectiveness and efficiency. While other methods of road cleaning involve manual or automated approaches, which may be less effective or complex, respectively, the proposed method employs a four-wheel drive mechanical chassis coupled with an embedded control system based on an ESP32 microcontroller, thus ensuring reliable functioning of both manual and semi-automatic modes. The innovative aspect of this research is that it provides an optimal configuration of the design elements that allow obtaining minimal costs while ensuring efficient mechanical components, low power consumption, and cleaning effectiveness by using high torque DC gear motors and rotating brushes. The evaluation of the performance of the system under investigation is carried out not only based on the results of performance tests but also through the comparison of the efficiency of road sweeping and the time required for cleaning by manual and automatic systems.

2. LITERATURE REVIEW

Recent research in cleaning robotics has emphasized improving efficiency, adaptability, and automation through advanced system architectures and intelligent control strategies. Kim et al. [5] proposed an autonomous robot vacuum system with a dual-robot architecture, where one unit performs cleaning while another handles waste collection. As a result, operational efficiency and dust storage capacity can be significantly improved. However, the overall system complexity and cost rise because of the many coordinated robots involved. Unlike K. Soni [6], who designed and constructed an autonomous smart floor

cleaning robot using basic control mechanisms embedded systems simply and inexpensively. Although it is effective for the indoor environment, it is not applicable for outdoor road cleaning due to navigation problems as well as environmental problems.

More advances saw the development of autonomous robotic vacuum systems [7], programmed to control and offer features for users, including automated dry and wet cleaning. Systems like Roomba and Dyson are usually for indoors and are not rugged enough for outdoors, which have uneven terrains. Z. The authors Liu *et al.* [8] proposed a design method for sweeping robots using fuzzy Quality Function Deployment (QFD) and ARIZ techniques. The objective is to optimize design parameters based on user requirements. Although this method improves the performance of the system and customizes it, and it creates extra-delivery and friction reduction for stable motion.

Similarly, [9] developed an autonomous mobile cleaning robot based on adaptive manufacturing and validated control algorithms. As per the research, stability and cost competitiveness were proven, but the system depends on navigation mechanisms that are autonomous and might complicate implementation for large-scale outdoor use.

$$F_t = (P_{motor} \times \eta) / v \tag{1}$$

where, F_t is tractive force of the motor, P_{motor} is Power output of motor and v is the linear velocity

The linear velocity of the sweeping machine is calculated as

$$v = 2\pi rN / 60 \tag{2}$$

where F is the force (N), T is the motor torque (Nm), and r is the wheel radius (m). This equation determines the load-handling capability and mobility of the system [1].

Currently utilized techniques of street cleaning face a number of drawbacks which affect their effectiveness and applicability in practice. Manual sweeping is rather inefficient in terms of the effort required, time spent, and performance reliability; moreover, it exposes workers to risks associated with dust inhalation and traffic. Automated sweeping machines, despite their efficiency, represent an expensive option which requires complicated maintenance, which makes them unsuitable for small towns and developing countries. Besides, some of the currently developed robots are meant for indoor utilization only and cannot work properly outside due to the complexity of navigation. Moreover, robotic sweepers are quite costly because of the complexity of their construction; at the same time, they consume much power and are unable to deal with different road conditions such as wet roads. Hence, there is a need to develop a cheaper, simpler, and partially automated technology. Innovative progress in cleaning robot design, control, and optimization was found in the studies. Nevertheless, most systems either emphasize full automation or indoor applications, with limited focus on developing simple, cost-effective, and semi-automatic solutions suitable for real-world road cleaning environments. This limitation motivates the need for a balanced approach integrating mechanical simplicity with embedded control, as proposed in this work.

3. PROPOSED METHODOLOGY

The proposed semi-automatic road sweeping system is developed by integrating mechanical design, electrical

components, and embedded control to achieve efficient and cost-effective road cleaning. In Figure 1, the system consists of a four-wheel drive mechanism powered by four 12V high-torque DC gear motors, enabling smooth multi-directional movement such as forward, reverse, left, and right. An additional DC motor drives a rotating brush mechanism that performs dust and debris removal from the road surface.

The system uses the ESP32 controller for processing inputs from the user and controlling the motors using the relay board, allowing both manual and semi-automatic control modes. Power supply to the system is provided using a 12V, 7 Ah battery to make sure that it remains portable and operates long enough. Some important performance specifications like the magnitude of force generated, torque, and the rate of movement are calculated using standard mechanical formulas to provide a perfect design. Lastly, experimental evaluations are done on the system for assessing its efficiency and speed among other factors.

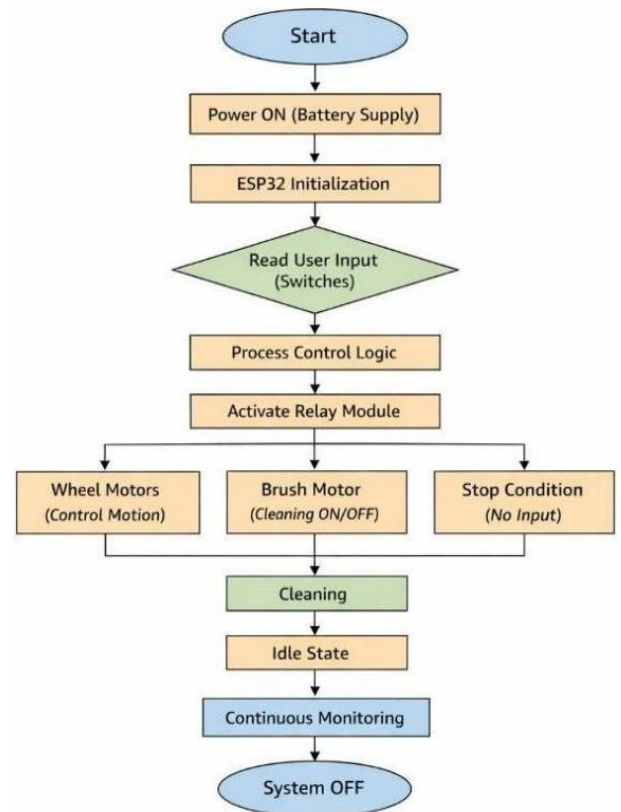


Fig.1. Flowchart of the semi-automatic road sweeping system showing control logic and operational sequence.

The control architecture consists of an ESP32 processor receiving the input signal from a manual switch to execute a control signal from the relay module. The performance of the system is evaluated using basic mechanical relationships. The tractive force generated by the motor is given by

The relay module is used for low-power control with high-power motor switching. According to user input, ESP32 operates relays to control wheel motion and brush operation. The system uses a 12V, 7Ah lead-acid battery. Spur gears and ball bearings are used for torque. where v is velocity (m/s), r is wheel radius (m), and N is motor speed (RPM). This relation is essential for analyzing operational speed during cleaning [2].

The overall methodology includes system design, hardware integration, control programming, and real-time performance evaluation to ensure a compact, reliable, and efficient cleaning solution.

4. RESULTS AND DISCUSSION

The functional evaluation of a fabricated semi-automatic road sweeping system was conducted under real-time conditions for performance effectiveness in terms of mobility, cleaning efficiency, power consumption and uptime. The system easily performs its operation by using four 12V DC motors, which can give a torque of nearly 2.94 Nm. The torque is increased to 5.88 Nm by reduction using a spur gear. Due to this improved torque, it was possible to operate effectively under moderate load conditions. A load of 8–10 kg was observed, which was close to the theoretical calculations. The semi-automatic road sweeper system that was designed was subjected to experimental testing in order to confirm the effectiveness of the design. The road sweeper utilizes four 12V high torque DC gear motors for its locomotion capability, and the total torque output after gearing is estimated at 5.88 Nm. The road sweeping functionality is performed by a DC motor-powered rotating brush which can clean dust and debris on the surface. The controller uses an ESP32 microcontroller which communicates with the relay modules for controlling the DC gear motors by using low power signals. The system is operated using a 12V 7 Ah lead-acid battery with a runtime period of 45-50 minutes.

The system works perfectly for road cleaning as the thermal oxidizer system has sufficient time for the brush interaction with the surface. The apparatus can work at around 1.3 km/hr operational speed. In dry conditions, the cleaning efficiency recorded is approximately, 88% meaning it could easily remove dust and small debris. While useful on wet or muddy soil, they prove less effective because they do not apply suction or water assistance. The model's control system utilized an ESP32, which reacted to user instructions correctly. A relay module was used to operate the motor without any delay in operations.

It provides 45–50 minutes of continuous operation with a 12V battery. Runs at approximately 1.3 km/h, ensuring thorough and uniform cleaning. Minimizes human exposure to dust and pollutants, ensuring better health and safer working conditions. Manual cleaning costs ≈ ₹500/day/person (~₹15,000/month), whereas this system can reduce labour dependency by up to 70–80%, significantly lowering operational expenses

The system's total power consumption was measured at 100–110 W, which is close to its theoretical value of 107.5 W. The pack was able to run for 45-50 minutes, confirming the model of energy consumption. Despite these advantages, some limitations were observed, which included dependency of the robot on manual navigation, decreased performance for sticky waste, etc.

Table.1. Specifications of parameters

Parameter	Manual System	Automatic System	Proposed System
Cleaning Efficiency (%)	55%	92%	88%
Power Consumption (W)	0	220	105

Speed (km/h)	0.5	3.0	1.3
Human Effort (%)	100%	10%	30%

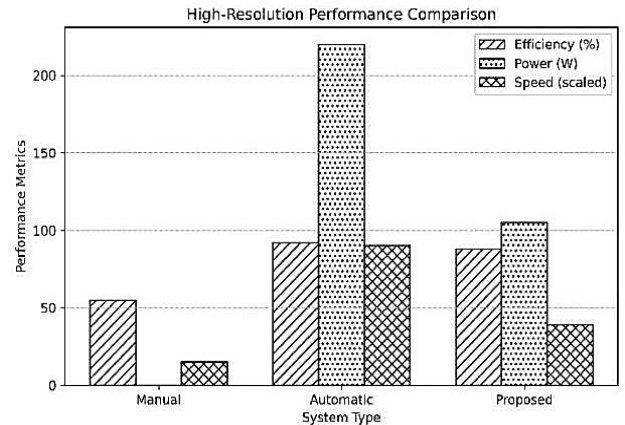


Fig.2.High-resolution performance

The results confirm that the proposed system significantly improves cleaning efficiency compared to manual methods, achieving an approximate 60% improvement:

In addition, power consumption is lowered by nearly 52 percent as compared to the fully automated system, which makes it energy efficient. A close agreement between experiment and theory shows the design methodology and system reliability. The connection between the mechanical elements and the embedded command guarantees performance plus cost plus usability, making it a proper system for real-world site- cleaning applications.

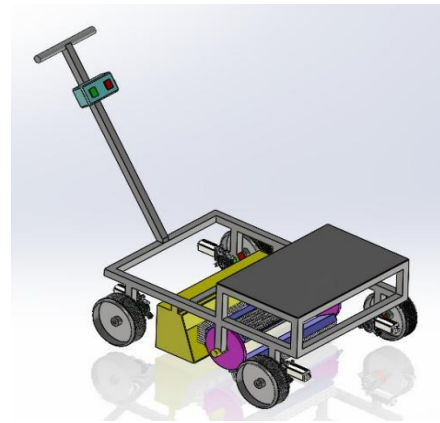


Fig.3. Mechanical Design Front view

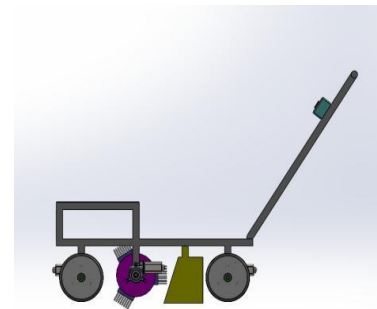


Fig.4. Mechanical Design side view

The mechanical design of the proposed system consists of a compact four-wheel mobile platform built on a rigid rectangular chassis frame. The structure is designed to provide stability and support for all components, including the drive system, sensing unit, and processing modules. The vehicle is powered by motor-driven wheels that enable smooth forward and backward movement. A rotating mechanism is mounted beneath the chassis, which is responsible for performing the core operation (such as cleaning, scanning, or inspection depending on application). This mechanism is driven by a dedicated motor to ensure continuous and efficient operation. Additionally, a front-mounted adjustable handle supports the placement of control switches and indicators, allowing easy manual operation and monitoring. The design ensures proper weight distribution, durability, and ease of maintenance, making the system suitable for real-time practical applications.



Fig.5. Sweeping System



Fig.6. Drive unit

Based on the experimental findings, the prototype has proven to have an efficiency of around 88% when cleaning dry surfaces with an average speed of 1.3 km/h, guaranteeing even distribution of the cleaning process. The system's total energy consumption is estimated to be approximately 100–110 W, confirming the initial theoretical calculations, thereby validating its accurate design. It can carry up to 8–10 kg of load, confirming sufficient mechanical resistance and stability. The new system is far more efficient in

terms of reducing human labor efforts (around 70–80%) compared to traditional manual methods and consumes considerably less power than fully automated cleaning systems.

5. CONCLUSION

The design, fabrication, and testing of a semi-automatic road sweeping system, which is presently movable, energy efficient and highly effective in cleaning. Under dry conditions, the system managed to clean about 88%, which is considerably greater than that of the manual methods, while requiring less power (~105 W) than fully automated ones. The rotating brush removes debris, while the four-wheel drive system gives the wheelbarrow stable motion and good load capacity. The controlling system based on ESP32 provides reliable working through easy switching based on a relay. The system was found to be reliant on manual navigation, inefficient during rainy weather and limited in battery backup. Still, the device is quite balanced in cost, efficiency and use. In conclusion, the device possesses a very practical and scalable way of cleaning roads and has a lot of room for future additions like automating, better cleaning solutions and smart monitoring systems with IoT connectivity.

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